ON THE CROSS CORRELATION BETWEEN THE ARRIVAL DIRECTION OF ULTRA-HIGH ENERGY COSMIC RAYS, BL LACERTAE, AND EGRET DETECTIONS: A NEW WAY TO IDENTIFY EGRET SOURCES?

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ABSTRACT

With the aim of testing recent claims for a particularly strong correlation between ultra-high energy cosmic rays (UHECRs), observed with the AGASA and the Yakutsk experiments, and a sample of BL Lacertae (BL Lacs), we here conduct a blind statistical assessment. We search for associations between the same set of BL Lac objects and the arrival directions of 33 relevant UHECRs observed with the Haverah Park and the Volcano Ranch experiments. Within the accuracy of angle determination, there are no positional coincidences. The probability that this null result arises as a statistical fluctuation from the strongly correlated case is less than 5%. This implies that the possible correlation between the arrival directions of UHECRs and BL Lacs is not statistically sustained. We discuss the impact of our findings on the propose additional connection among UHECRs, BL Lacs, and EGRET γ-ray blazars. Recently, such an association was used as classification technique for EGRET sources. Here we show that its main underlying hypothesis, i.e., the EGRET angular uncertainty is twice that quoted in the Third EGRET Catalog, grossly underestimates the goodness of existing gamma ray data.

Subject headings: Ultra-high energy cosmic rays – BL Lacertae – gamma rays NUB-3238-TH-03

1. INTRODUCTION

Farrar and Biermann (1998) pointed out the existence of a directional correlation between compact radio quasars (QSOs) and ultra-high energy cosmic rays (UHECRs). Their claim was supported by two significant factors: (i) there was an *a priori* postulated theoretical reason by which to expect such an alignment, i.e. the existence of a new neutral hadron that would travel unscathed all the way to the Earth (Farrar 1996, Chung et al. 1998) or neutrinos producing Z-bursts (Weiler 1999; Fargion, Mele & Salis 1999; Fodor, Katz & Ringwald 2002), and (ii) all events at the high end of the spectrum observed by that time, with energy at least 1σ above $10^{19.9}$ eV, were aligned with high redshifted quasars, a phenomenon with a chance probability of occurrence less than 0.5% (Farrar & Biermann 1998). This report quickly opened a large debate on whether UHECRs can evade interactions with cosmic microwave background photons, and arrive at Earth evading the Greisen (1966) – Zatsepin–Kuzmin (1966), GZK, cutoff. Most of the alternative explanations to evade the GZK cutoff require physics beyond the standard model (for an exception see Kalashev et al. 2001), including violation of local Lorentz invariance (Coleman & Glashow 1998), photon-axion mixing (Csaki et al. 2003), and neutrinos interacting strongly in the atmosphere (due to physics beyond the –perturbative– Standard Model, Fodor et al. 2003; or because of TeV-scale gravity, Domokos & Kovesi-Domokos 1999, Jain et al. 2000). The latter, however, is severely constrained by observations (Anchordoqui et al. 2001). In this *Letter*, we first comment on the status of the correlation between QSOs and UHECRs, and then analyze more recent strong claims for a correlation between UHECRs and BL Lacertae (BL Lacs), a subgroup of the previously studied QSOs. Finally, we scrutinize a newly proposed classification technique of EGRET sources, based on the cross correlation of BL Lacs, UHECRs, and γ-ray catalogs.

2. QSOS AND UHECRS

The possible correlation between UHECRs and QSOs was subject to a great deal of scrutiny. Hoffman (1999) stated that one of the 5 events used in the Farrar and Biermann (1998) study, the highest energy event observed by the Fly's Eye experiment (Bird et al. 1995), should not be included in the UHECR sample under analysis, because this very same event was previously considered to introduce the hypothesis. Without this event, the positive alignment with random background probability is increased to $< 3\%$ (Farrar & Biermann 1999). Using an updated event list (twice the size of the previous) from the Haverah Park (Ave et al. 2000) and the AGASA (Hayashida et al. 2000) experiments, Sigl et al. (2001) showed that the statistical significance of the alignment is lowered to 27%. More recently, Virmani et al. (2002) favored the earlier proposed alignment. However, it should be stressed that most of the Virmani et al. correlation signal comes from events with large uncertainty both in energy and in position: they considered events from the SUGAR experiment, but it is not clear whether these events were above the GZK cut-off (see, e.g., Anchordoqui et al. 2003).

Very recently, the Haverah Park energy estimates have been re-assessed (Ave et al. 2003). For the cosmic rays in question, the energy of the 2 events observed by this array with incident zenith angle $< 45^\circ$, that was previously quoted as $> 10^{19.9}$ eV at 1σ, is now shifted $\approx 30\%$ downwards, below the energy cut chosen by Farrar and Biermann (1998). Hence, independently of the statistical test used, when considering only the high-

est energy ($> 10^{19.9}$ eV at 1σ) events[1] the correlation between UHECRs and QSOs is consistent with a random distribution at the 1σ level.

3. BL LACS AND UHECRS

In a series of recent papers, Tinyakov and Tkachev (2001, 2002, 2003) claim a correlation between the arrival directions of UHECRs and BL Lacs, a subgroup of the QSO sample previously considered. Specifically, the BL Lacs chosen were those identified in the (9th-Edition) Veron-Cetty and Veron (2000) catalogue of Quasars and Active Galactic Nuclei, with redshift $z > 0.1$ or unknown, magnitude $m < 18$, and radio flux at 6 GHz $F_6 > 0.17$ Jy.[2] Only 22 objects fulfill such restrictions. In this analysis there is no buffer against contamination by mismeasured protons piled up at the GZK energy limit. The CR sample of Tinyakov and Tkachev consists of 26 events measured by the Yakutsk experiment with energy $> 10^{19.38}$ eV (Afanasiev et al. 1996), and 39 events measured by the AGASA experiment with energy $> 10^{19.68}$ eV (Hayashida et al. 2000). The evidence supporting their claim is based on 6 events reported by the AGASA Collaboration (all with average energy $< 10^{19.9}$ eV), and 2 events recorded with the Yakutsk experiment (both with average energy $< 10^{19.6}$ eV), which were found to be within 2.5° of 5 BL Lacs contained in the restricted sample of 22 sources. The chance probability for this coincidence set-up is found to be 2×10^{-5}.

One drawback of the claim made by Tinyakov and Tkachev (2001) is that the data set used to make the initial assertion is also being used in the hypothesis testing phase. Note that if enough searches are performed on a finite data set which is sampled from an isotropic distribution, some highly significant positive results are certain to occur due to the statistical fluctuations that necessarily arise in any finite sampling. Evans, Ferrer and Sarkar (2002) already called into question whether the selection criteria for the subset of brightest BL Lacs are unbiased. Strictly speaking, Tinyakov and Tkachev imposed arbitrary cuts on the BL Lac catalogue so as to maximize the signal-to-noise ratio, compensating *a posteriori* the different cut adjustments by inclusion of a penalty factor. Without these arbitrary cuts, the significance of the correlation signal is reduced at the 1σ level (Evans, Ferrer & Sarkar 2002). Moreover, even in acceptance of this *a posteriori* approach, the estimated value of the penalty factor is subject to debate (Evans, Ferrer & Sarkar 2002; Tinyakov & Tkachev 2003).

Given the pivotal role played by the penalty factor in testing the hypothesis with a single set of data, it is of interest to circumvent this ambiguity by performing a blind analysis. We have at our disposal the cosmic ray arrival directions of the Haverah Park (Stanev et al. 1995) and Volcano Ranch (Linsley 1980) experiments, which, although not useful to distinguish a positive correlation (because the penalties involved are probably already as large as the signal which one expects to test), they provide the framework to disregard the correlation if none is found in the data.

Surface arrays in stable operation have nearly continuous observation over the entire year, yielding a uniform exposure in right ascension. However, the declination distribution is different for each experiment, because the relative efficiency of the detection of events depends upon the latitude of the array and detector type. As shown by Uchihori et al. (2000), the field of view of AGASA + Yakutsk is roughly equal to that of Volcano Ranch + Haverah Park. It is noteworthy that even though the energy of the Haverah Park events has been reduced by about 30% (Ave et al. 2003), the 27 events contained in our sample, originally with energy $> 10^{19.6}$ eV (Lawrence, Reid & Watson 1991), are well above the energy cut for Yakutsk's events selected by Tinyakov and Tkachev. Combined with the 6 events recorded at the Volcano Ranch with energy $> 10^{19.6}$ eV (Linsley 1980), we have a virgin data-set of 33 events, amounting to half of the cosmic-ray arrival directions used to make the claim.

In Fig. 1 we plot the position on the sky in galactic coordinates of both the UHECRs and the selected BL Lacs. There are no positional coincidences between these two samples up to an angular bin $> 5^\circ$. Such an angular scale is well beyond the error in arrival determination, which is found to be $\approx 3^\circ$ (Uchihori et al. 2000). On the basis of the strongly correlated sample analyzed by Tinyakov and Tkachev, one expects the distribution describing the correlation between the set of BL Lacs and any UHECR data-set with 33 entries to be Poisson with mean ≈ 4.06. Taking the data at face value, this implies a 2σ deviation effect. Moreover, the 95% CL interval of the distribution which samples the correlation between the BL Lacs and cosmic rays recorded by Volcano Ranch + Haverah Park is (0, 3.09) (see, e.g. Feldman & Cousins 1998). Therefore, the probability to measure the expected mean value ≈ 4.06 is $\ll 5\%$. All in all, the 8 coincidences in the Tinyakov and Tkachev (2001) analysis do not represent a statistically significant effect.

4. UHECRS AND EGRET AGNS

On a similar track, Gorbunov et al. (2002) claimed that a set of γ-ray loud BL Lac objects can be selected by intersecting the EGRET and BL Lacs catalogs. The only requirement that Gorbunov et al. considered for a BL Lac to be physically associated with an EGRET source is that the angular distance between the best estimated position of the pair does not exceed $2R_{95}$, where R_{95} is the 95% CL contour of the EGRET detection.

Their claim was based on a positional correlation analysis (using the doubled size for EGRET sources) between the Third EGRET Catalog (3EG, Hartman et al. 1999) and the objects identified as BL Lac in the Veron-Cetty & Veron (2000) Catalog. This results in 14 coincidences, 4 of which are further found to be part of the 5 BL Lacs located within 2.5° of UHECRs discussed above.

The typical R_{95} radius for EGRET sources is 0.5–1°. Because of such large uncertainties, a standard practice in γ-ray studies aiming to give preliminary associations between EGRET sources and possible counterparts is to study, in addition to the object being proposed, any other coincident system able to generate photons in the EGRET range (100 MeV–10 GeV). All of the latter should be discarded as the origin of the high energy radiation in order for the association claim to persist. This process usually involves theoretical modelling and multiwavelength observations (see e.g. Caraveo 2002, Reimer et al. 2001, Torres et al. 2003a, and references therein).

The case of active galactic nuclei (AGNs) as EGRET counterparts has been analyzed by Mattox, Hartman and Reimer (2001), who provided a spatial-statistical assessment. They list

[1] Those events would be most interesting for new physics, because they have no contamination from the expected proton pile-up around the photopion production threshold.

[2] The catalogue of Quasars and Active Galactic Nuclei is regularly updated, see Veron-Cetty and Veron (2001) for the 10th-Edition. The 9th-Edition is electronically available at `http://www.obs-hp.fr/www/catalogues/veron2_9/veron2_9.html`.

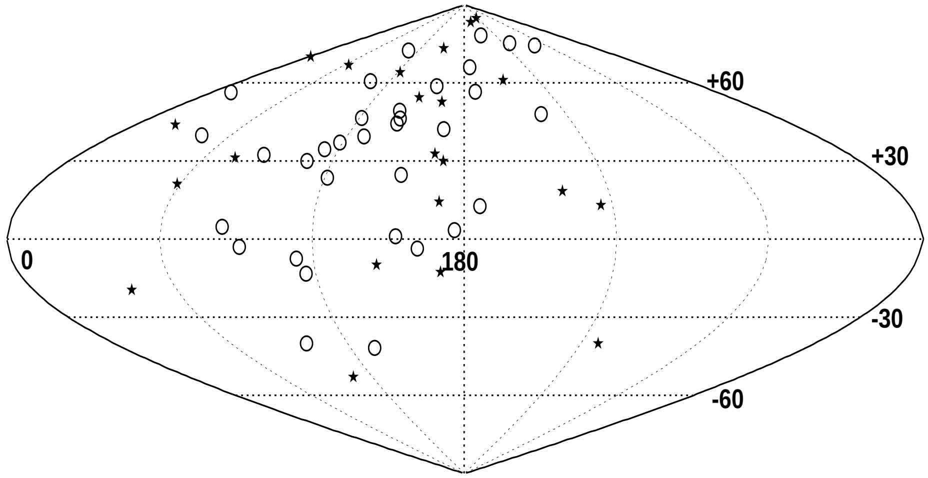

FIG. 1.— The open circles indicate the arrival direction (in galactic coordinates, l and b) of 33 UHECRs with incident zenith angle $< 45°$ observed by the Haverah Park (27 events) and the Volcano Ranch (6 events) arrays. There are two sets of CRs clustering within experimental angular resolution (Uchihori et al. 2000). Namely, a Haverah Park doublet with coordinates ($l = 140.98°$, $b = 49.43°$) + ($l = 143.60°$, $b = 46.30°$) and a mix-doublet Volcano Ranch ($l = 143.00°$, $b = 44.30°$) + Haverah Park ($l = 143.60°$, $b = 46.30°$). The stars stand for the 22 BL Lacs from the 9th-Edition of the Veron-Cetty and Veron (2000) catalogue of Quasars and Active Galactic Nuclei, with redshift $z > 0.1$ or unknown, magnitude $m < 18$, and radio flux at 6 GHz $F_6 > 0.17$ Jy.

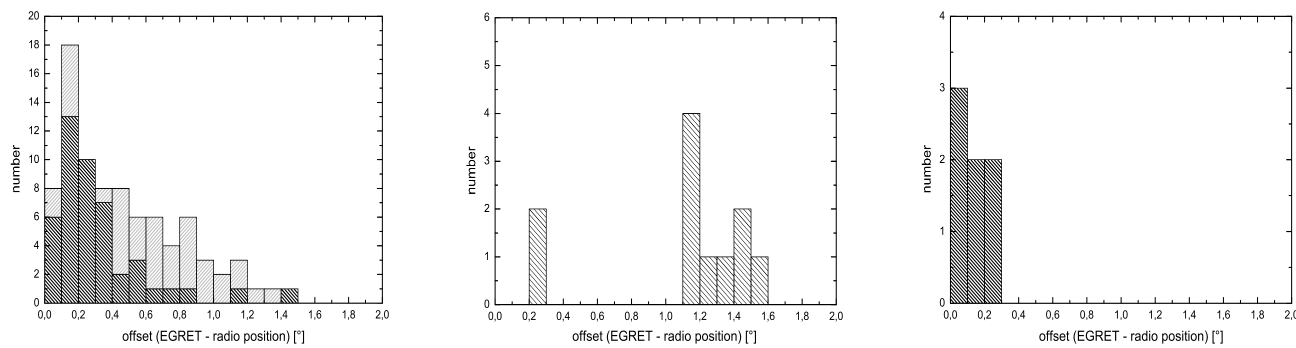

FIG. 2.— Left: Offset distribution between γ-ray and radio position of high-confidence [dark histogram] and plausible [light histogram] 3EG-classified AGNs. Middle: Offset distribution for the newly proposed associations using the Gorbunov at al. technique (see text). Right: Offset distribution for 3EG pulsars.

46 EGRET sources with high probability of being identified with known blazars, confirming 45 AGN identifications made in the 3EG (Hartman et al. 1999). A further 39 EGRET sources have been listed as plausible AGN identifcations. In Fig. 2 (left panel) we show the positional offset between the maximum-likelihood-algorithm for the γ-ray source position (Mattox et al. 1996) and the radio position of the respective AGN identification. We show separately those AGN considered as high-confidence and plausible counterparts.

Independent support for some of these AGN identifications results from dedicated multifrequency counterpart observations, including spectroscopic confirmation of their blazar nature (Sowards-Emmerd, Romani & Michelson 2003, Halpern, Eracleous & Mattox 2003). In contrast to the offset distribution between γ-ray and radio position of confirmed (or at least, most probable) AGN identifications, the offset distribution of the newly suggested AGN counterparts by Gorbunov et al. (2002), shown in Fig. 2 (middle panel), has a completely different shape. We attribute this to the inappropriate consideration of source localization uncertainties of EGRET-detected γ-ray sources, which lead Gorbunov et al. to suggest counterparts well into the range of $2R_{95}$ of an individual EGRET source. This extension of the EGRET angular uncertainty was motivated in a discrepancy between the radio and the γ-ray position of the Vela pulsar, which will be discussed below. For comparison, Fig. 2 (right panel) gives the offset distribution for the radio and γ-ray positions of identified pulsars in the EGRET data. Clearly, the range of absolute offset values, based on phase selected γ-ray events, is minimal in the case of the pulsars.

The 3EG source related to Vela is a very special case. It is the strongest known γ-ray source, and one of the best localized, $R_{95} = 0.021°$. The 95% CL contour of the EGRET detection and the offset with Vela are both one order of magnitude less than the typical values of these quantities in the 3EG. The misplacing for Vela occurs because the analysis technique privileges the discovery and correct detection of weaker sources, and it is applied to all EGRET sources in the 3EG (2/3 of which are unidentified with no obvious candidates) identically. The offset of the Vela position and, in general, of bright sources, is minimized by using map bins smaller than the standard 0.5° used in

the 3EG. This increases the computation time greatly; and since all of the most significant sources were identified with objects whose positions were well known, the smaller bin size was not adopted to give source positions in the 3EG. See the comment on the source 3EG J0834-4511 (Vela) in the section of particular detections of the 3EG Catalog (Hartman et al. 1999). Systematics, then, do not pose a major problem for the source location capability of EGRET, even in regions of significant diffuse emission or strong nearby sources (Hartman et al. 1999). Most importantly, the error contours for many of the AGNs show that the location capability improves for regions away from the Galactic plane, where most of the blazars are.

In addition, some of the 3EG-associated AGNs could be false positives (i.e. AGNs that are mis-associated with EGRET sources by a failure of the statistical methods used in the classification). This fact is particularly important for statistical methods based *only* on the relative positions between the candidate and the EGRET source center (see Torres 2003b for a review). Working with 114 sources above $|b| > 10^o$, Punsly (1997) has estimated the number of random coincidences as a function of the field radius: ~ 2 (10) quasars with more than 1 Jy of 5 GHz flux are expected to correlate by random chance if the size of the typical EGRET angular uncertainty is 0.7^o (1.7^o). The number of random coincidences increases as the radio-loudness of the AGN decreases (since there are more AGNs with smaller flux). This sheds additional doubt on the correlations found beyond the 95% location contours of EGRET sources.

5. CONCLUDING REMARKS

Available statistics on the arrival directions of the UHECRs reveals no significant correlations above random with BL Lacs nor with any other type of quasars, including EGRET blazar detections. Furthermore, identifying EGRET sources with BL Lacs just by positional pairing within twice the EGRET error grossly underestimates the goodness of existing gamma-ray data. [3]

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[3] In closing, we comment on the apparent correlation between nearby dormant quasar remnants ("dead quasars") and the arrival directions of the 38 UHECRs measured by the AGASA experiment with energy $> 10^{19.6}$ eV and $|b| > 20^\circ$ (Torres et al. 2002). We note that NGC 2300 (which is the only quasar remnant hosted in a non-elliptical galaxy) is actually beyond the reach of the AGASA experiment, which improves a little the correlation presented by Torres et al. (2002). Since there are 25 events with $|b| > 20^\circ$ (some of them with energy $< 10^{19.6}$ eV) in the data sample which combines measurements of the Volcano Ranch and the Haverah Park experiments, the dead quasar hypothesis (Boldt & Ghosh 1999) is limited by the statistics of small numbers (the expected mean value being ≈ 1.31 is just on the verge of the 68.27% CL interval, Feldman & Cousins 1998), and the hypothesis awaits further testing with larger sets of data.